The spatial repeatability of dynamic pavement loads caused by heavy goods vehicles

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For some time it has been suspected that the higher-than-average dynamic loads imposed on roads by heavy vehicles cluster at particular positions along a road. This was first suggested by Hahn and simulation by Cole has confirmed that this is likely. This paper presents experimental evidence on the degree of clustering that occurs and indicates the extent to which this increases road wear.

TRL has measured dynamic pavement loads for a variety of vehicles, suspension types and speeds on three sections of the TRL research track. These measurements have been used to determine the loading pattern along the track for each vehicle, suspension and speed. The applied loads have been summed for typically 50 - 100 different axle passes and the total and mean applied loads at each station calculated. This analysis of the experimentally measured dynamic loads suggests that load concentration points do occur at which the mean load is at least 5 percent greater than the static load. This load concentration effect would double the significance of dynamic loads as a cause of excess road wear, relative to that estimated by the method of Eisenmann.

Three sections of public roads have been instrumented with strain gauges in each wheel track at 1 metre intervals over a length of 60 metres. These have been used to measure the horizontal strains at each of the 60 stations. Typical measurements are shown in the paper. At the time of writing the analysis of the total loads and load concentrations along the road sections has not been completed. One section of public road has been instrumented with eight weigh-in-motion sensors at 2.7 metre intervals in each wheel track. These have been used to measure the local loads applied by over 2000 HGV axles. The preliminary analysis of these results suggests that average loads vary by ± 20% along the instrumented section, and that the pattern of load concentration points has been stable over a five month period.

1 INTRODUCTION

It has been known for many years that heavy vehicles bounce when they are in motion, and that the dynamic loading pattern imposed on the road surface is highly repeatable for a given vehicle at a given speed. Hahn has suggested (1987) that because many heavy vehicles have similar dynamic characteristics and travel at similar speeds on a given stretch of road, then the above-average pavement loads caused by the dynamic bouncing of all the vehicles in a stream of traffic may concentrate at particular points along a section of road.

The degree to which high dynamic loads are concentrated spatially under real traffic has important implications for the road wear caused by dynamic bouncing. If dynamic loading patterns were to repeat exactly, at points of high loading the road wear would be increased by the fourth power of the local impact factor. Since impact factors of 1.3 to 1.5 are common, the implied increase in local road wear would be by a factor of 2.8 to 5. If, on the other hand, points of high loading under different vehicles were distributed randomly along the road, Eisenmann (1975) has shown that the road wear would increase as the variance of the dynamic loads. The impact factors quoted above would correspond to dynamic load coefficients (rms dynamic load/static load) of about 0.15 to 0.25, and the increase in road wear would be about 13% to 38%.

Cole (1990) has shown by computer simulation that a degree of spatial concentration of dynamic loads is likely to occur under streams of typical heavy goods vehicles. This paper reviews the experimental evidence for the spatial concentration of high dynamic loads, and provides an estimate of the effect of dynamic bouncing on the wear of one length of public road.

2 REPEATABILITY UNDER TEST CONDITIONS

When a vehicle is run over a given length of road at a set speed the dynamic loading is extremely repeatable.

Figure 1 shows the loads under a wheel on the front and a wheel on the drive axle of a 2 axle HGV during four runs at 80 km/h on a public road. The traces show how closely the loads under each wheel repeat on each successive run, but of course the loads under the front wheel are not the same as those under the rear wheel. Although Figure 1 is plotted against a scale of time, the loads are located along the road by measuring the distance travelled by the vehicle.

The axle loads on the 2 axle HGV were measured on the same day. Figure 2 shows the dynamic loads under one wheel of a steel sprung semi-trailer bogie on the rough section of the TRL track. Two runs are shown at each of two speeds. The runs were made 16 months apart and the repeatability is reasonably good, though not as precise as that shown in Figure 1. Whether the differences are due to changes in the vehicle, its loading or the track is not known. The position along the track is estimated from the vehicle speed, so minor differences in speed cause small changes in the positions of load patterns. The relatively high degree of repeatability over more than a year shows that, at least on lightly trafficked roads, the pattern of dynamic loading for a given vehicle should not change over time.

Figures 1 and 2 show clearly the repeatability of dynamic loading under test conditions. This demonstrates that the dynamic motion of the vehicle is being forced by the road profile, and that self-excitation by tyre eccentricities have a second order effect on roads of the roughness used for these tests.

3 SPATIAL CONCENTRATION ON A TEST TRACK

Section 2 has shown the high level of repeatability for the dynamic loads under a given vehicle at a set speed. Of more practical concern is the

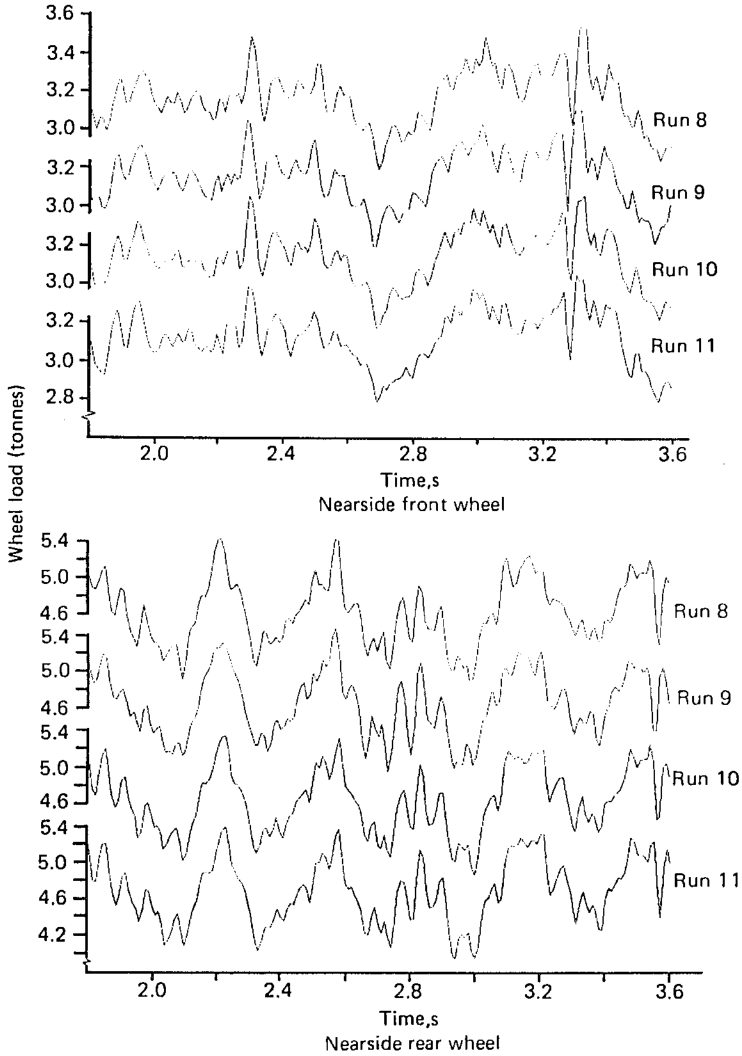

Fig.1 Dynamic wheel loads for a 2 axle HGV at 80 km/h on a trunk road

repeatability of dynamic loads under a mix of traffic with the range of speeds that occurs in practice. A first attempt to assess whether there are points of higher-than-average cumulative loading at points along a road has been made using wheel loads measured on instrumented vehicles on the TRL test track.

During its research on dynamic pavement loads TRL has measured wheel loads on a wide range of HGVs at speeds between 32 and 96 km/h on three sections of the test track (Mitchell, 1991). These results have been processed to represent loads along the track and summed for each vehicle/wheel/speed combination. This does not represent the variety of speeds and vehicle types in real traffic, but is merely a way of exploring whether load concentration points occur under an arbitrary mix of traffic and speeds.

Cumulative pavement loads at points along the track have been calculated by taking all the measurements for, say, bogies with steel leaf suspensions. At a given point a load is recorded for one wheel of each axle at each measurement speed. The cumulative load is then the sum of the loads at that point for all the wheels (one load per wheel) either at one speed or at all speeds. This process is repeated for many points along the track and a curve plotted of the variation of the cumulative load along the track. The number of wheels included in the cumulative loads at different speeds varies because not all bogies were tested at all speeds, or because transducers failed on some axles for some runs. For any one run, the number of wheel loads included was the same throughout the run.

Figure 3 shows the cumulative wheel load under 5 or 6 wheels of steel sprung semi-trailer bogies on the rough section of the TRL track. It can be seen that the sum of all the wheel loads varies substantially along the track. The wavelength tends to increase with increasing speed, but there are positions on the track where the loads are usually above average, particularly at the higher speeds. At track position 20.0 m the cumulative load is high at 64, 80 and 96 km/h. The same happens at 52.5 m and, at 80 and 96 km/h, at 83.3 m and 92.5 m.

It appears that particular aspects of the road profile force a particular dynamic response over a range of speeds. Thus between 60 m and 82 m there are 3 bounce cycles at 80 km/h but only 2 at 96 km/h. Where the natural response of the vehicle to the profile does not match the cyclical response, the variation in the wheel load becomes confused and the dynamic component small. For the steel sprung suspensions this happens between positions 25 m and 45 m at 96 km/h. Figure 4 shows similar results on the same rough section of the test track for between 5 and 7 axles of bogies with air suspensions.

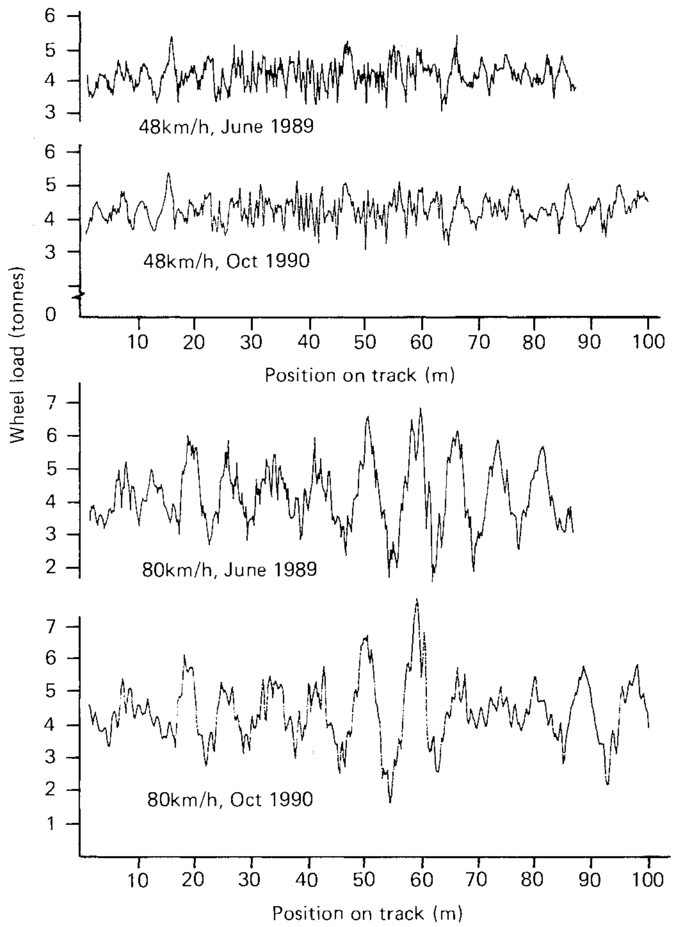

Fig.2 Dynamic loads for one wheel of a semi-trailer bogie on the TRL track (rough section)

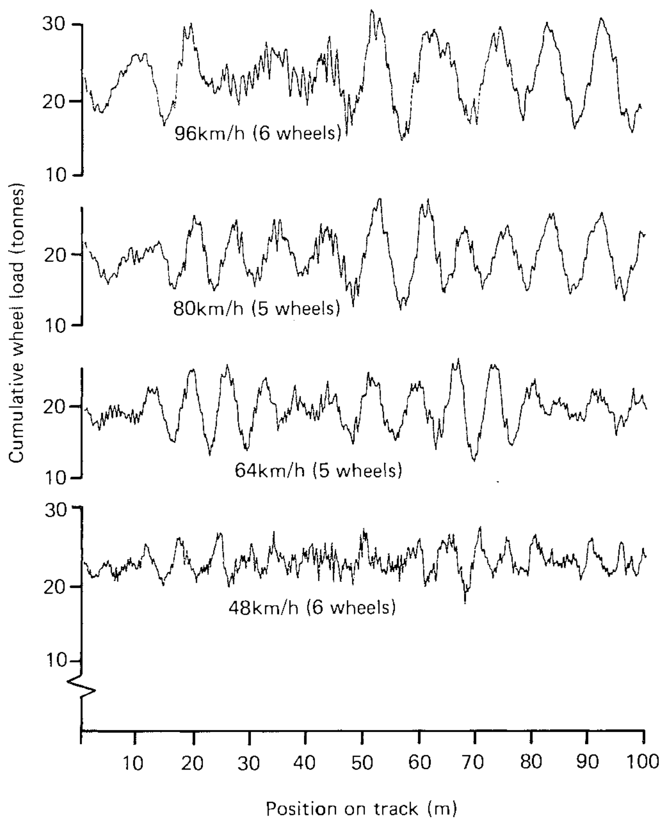

Fig.3 Sum of the loads under 5 or 6 wheels of steel sprung semi-trailer bogies on the TRL track (rough section)

Figure 5 shows the cumulative wheel loads summed for the steel sprung trailers at all speeds from 32 km/h to 96 km/h, for the air sprung trailers and for all axles at all speeds. This is not representative of typical traffic and the range of speeds is much greater than would be experienced in practice. Even so, the cumulative wheel load applied to the rough section of the track varies by about ± 15% over the 100 metre test length of the rough section. This variation is significantly greater than would be expected statistically if the high loads were distributed randomly along the track. (A single wheel has a dynamic load coefficient of about 20%, so the standard deviation of the sum of 64 uncorrelated wheel loads should be about 2½%)

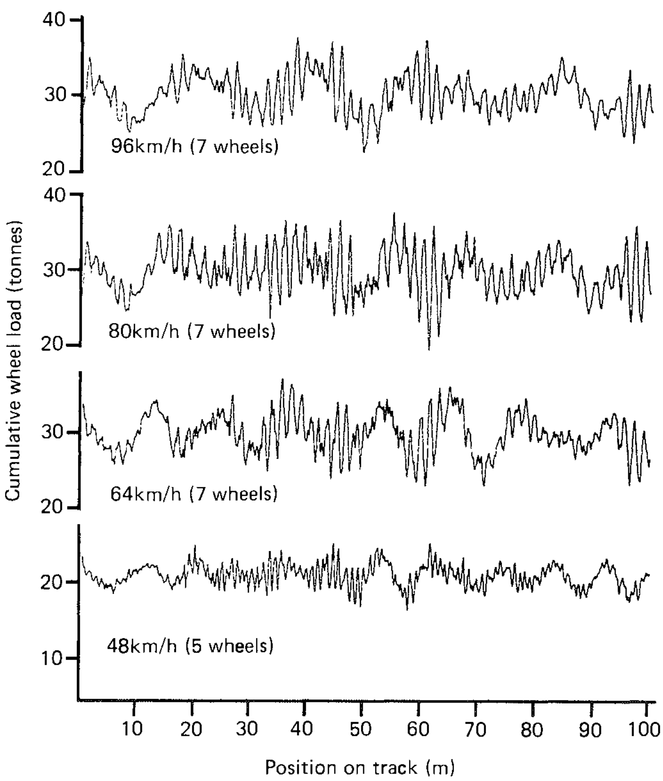

Fig.4 Sum of the loads under 5 or 7 wheels of air sprung semi-trailer bogies on the TRL track (rough section)

Figure 6 shows similar results for steel sprung bogies, air sprung bogies and all bogie wheels on a 400 metre length of medium unevenness asphalt pavement on the TRL track. Again a regular pattern of cumulative loads above and below average can be seen, in this case of about ± 9% about the average. The variation in cumulative loading shown in this figure is similar to that predicted by Cole (1990).

Although Figures 3 - 6 present results in terms of the varying total of all the local axle loads along a section of road, it would probably be better to present this information as the variation of the cumulative impact factor along the section. This is defined as the sum of all the wheel loads at one station divided by the sum of the static wheel loads. Where this is greater than 1.00, concentration of dynamic wheel loads is occurring.

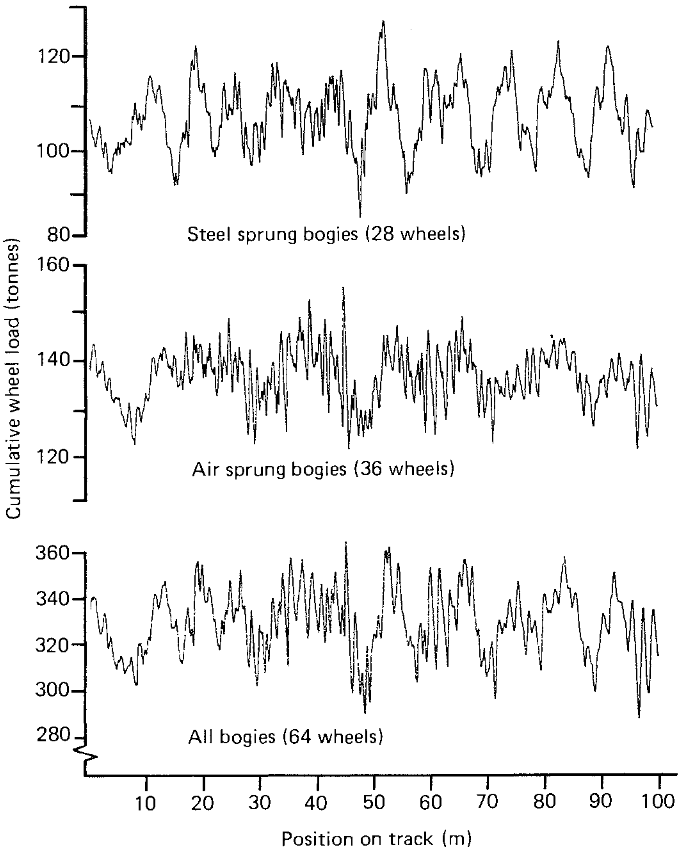

Fig.5 Sum of the loads under all the wheels of air and steel sprung semi-trailer bogies at speeds of 32 to 96km/h on the TRL track (rough section)

4 SPATIAL REPEATABILITY ON PUBLIC ROADS

4.1 Introduction

Public roads experience the full mix of types of vehicle and states of loading, and a range of traffic speeds. But simple estimates based on road wear being proportional to the fourth power of wheel loads suggest that in Britain about three quarters of all structural road wear is caused by articulated HGVs, and that only the vehicles that are more than about 70% laden contribute significantly (Mitchell and Gyenes, 1989). Since the vehicle geometries and axle loads are constrained by regulations, and tyre and spring stiffnesses are similar, it is likely that most of the HGVs that cause significant road wear are dynamically similar. Vehicles on steel and air springs will, of course, be dynamically different.

On trunk roads and motorways the speeds of HGVs are relatively constant on particular links. For example, at three dual carriageway sites, 56% of articulated HGVs were travelling at 50 - 60 mph and only 9% were travelling slower than 40 mph or faster than 65 mph. Similarly, at nine motorway sites, 81% were travelling at 50 - 65 mph. Given the similarity of the vehicles and the small range of speeds, it is not unlikely that dynamic loading patterns will tend to repeat. This section describes two attempts to measure this repetition.

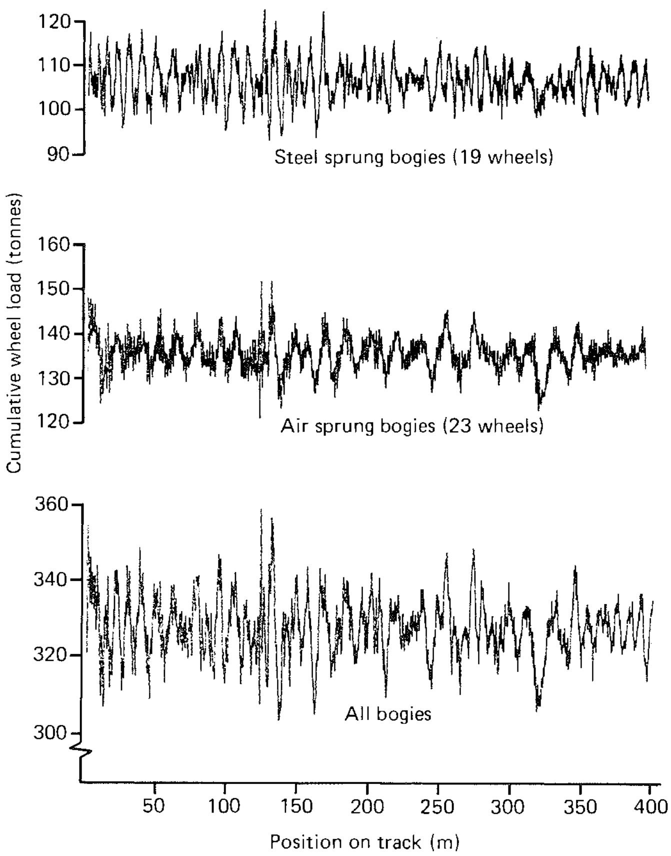

Fig.6 Sum of the loads under all the wheels of air and steel sprung semi-trailer bogies at speeds of 32 to 96km/h on the TRL track (medium section)

4.2 Strain gauged sections of public roads

Strain gauges have been fitted at a depth of about 300 mm to measure the longitudinal horizontal strain at the bottom of the structural layer of three sections of road (two trunk and one motorway). At each site there are 120 gauges, set in lines of 60 along each wheel track in the nearside lane at 1 metre spacing. A typical set of results from 9 gauges for the nearside wheels of three different 5 axle HGVs on the M4 motorway is shown in Figure 7. The strain peaks under the two axles of the tractors and the 3 axle trailer bogies can be clearly seen. The relative heights of the peaks vary as the vehicle bounces. Differences between the gains of the gauges and the recording system change the absolute height of the traces at the different stations.

Data such as this can be analysed by hand once the gains of the individual gauges are known, but the amount of work involved in doing this for hundreds of vehicles is formidable. Attempts to identify the strain peaks by computer and analyse the traces automatically have not succeeded to date. Data exist for many hundred axles at each site, and analysis of the data by one means or another will be carried out.

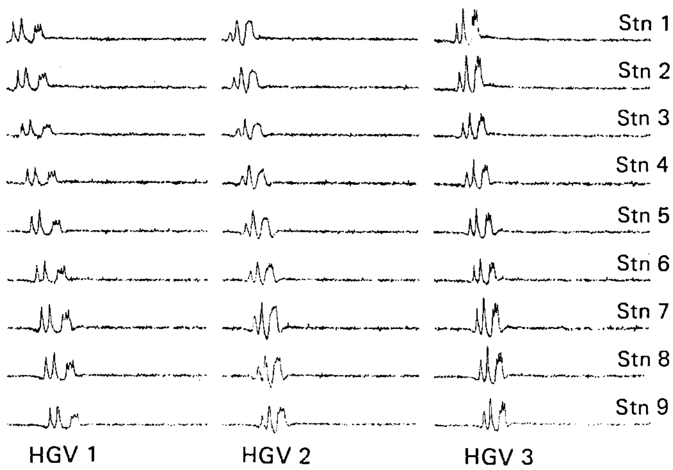

Fig. 7 Pavement strains at 9 stations on a motorway under the nearside wheels of 3 5 axle HGV

4.3 Multiple sensor Weigh-in-Motion measurements

One site on a trunk road has been instrumented with 8 weigh-in-motion strips in each wheel track at 2.7 metre intervals (Barbour and Newton, 1992). These have been calibrated using an instrumented 2 axle HGV (the traces in Figure 1 are four of the 7 runs used for calibration). Wheel loads have been collected since September 1991 and the summed wheel loads at the eight sensors for about 2000 axles show a variation of about ± 20% about the mean sum. Figure 8 shows preliminary results for the two wheel tracks for about 100 axles in each of September 1991 and February 1992. The results are only preliminary at the time of writing because it is necessary to confirm the calibrations of the sensors using a different instrumented HGV with more axles. Nevertheless, the preliminary results show that the pattern of load concentration points did not change greatly between September 1991 and February 1992.

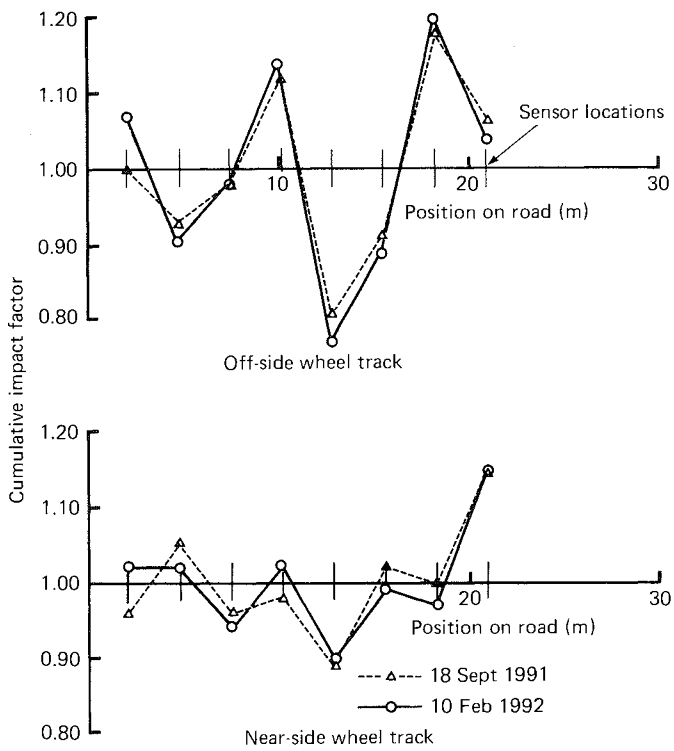

Fig.8 Cumulative impact factor for heavy vehicle wheels on a trunk road

It is noticable that the pattern of cumulative loading in the two wheel tracks is not the same. This may suggest that roll motion of either the vehicles or their axles is contributing significantly to the dynamic loads applied to the road surface, but until the calibration of the sensors has been confirmed it is too early to be certain about this. For the off-side wheel track, the cumulative loading shows a wavelength of about 8 metres. This is similar to that of the loads from semi-trailer bogies on the TRL track (Figures 3 - 6), and also to the pattern predicted theoretically by Cole (1990), though the size of the effect from the preliminary weigh-in-motion results is rather larger.

The implication of these results is that the spatial concentration of dynamic wheel loads is increasing the cumulative wheel loads at some points by about 20%. If road wear is proportional to the fourth power of the wheel loads, this implies a doubling of road wear over that due to rolling static loads.

5 DISCUSSION AND CONCLUSIONS

Experimental evidence has been presented of the repeatability of dynamic wheel loads under a given vehicle at a set speed. It has also been shown that reasonable repeatability occurs over a 16 month period on a test track.

When the dynamic loads under a number of wheels of HGVs with air and steel suspensions are summed at short intervals along a test track, the cumulative wheel load shows variations of typically ± 9% on a section of medium unevenness and ± 15% on a rough section. The variations in cumulative wheel loads show a wavelength of some 8 metres, and look similar to theoretical results obtained by Cole (1990) using computer simulation. The variation in the cumulative wheel load along the sections of the test track is much greater than would be expected statistically from uncorrelated, randomly varying, dynamic wheel loads. These results do not represent the loads under typical traffic, but do show that the dynamic loads under an arbitrary mix of vehicles over a range of speeds are not randomly distributed along a road.

Strain gauges have been used to measure the longitudinal pavement strain at 1 metre intervals along each wheel track of three sections of public roads. The strain signals obtained are excellent and allow the peak strains under each wheel of each vehicle to be measured for normal traffic. Analysis is still in progress to determine the cumulative pavement strains at each station along the instrumented sections of road.

Weigh-in-motion sensors have been used to measure wheel loads under normal traffic at eight stations in each wheel track on a public trunk road. These show variations in the cumulative wheel loads of about ± 20% over the length of the instrumented road. The pattern of load variations was reasonably constant between September 1991 and February 1992. There were substantial differences between the load concentrations in the off-side and near-side wheel tracks, but this is a provisional result pending further confirmation of the sensor calibration.

The general agreement between the theoretical predictions of cumulative loading made by Cole (1990), the cumulative loads on the TRL track derived from measurements with instrumented vehicles, and the cumulative loads measured on a trunk road under real traffic using weigh-in-motion sensors, indicates strongly that dynamic wheel loads do cluster significantly. On roads with medium unevenness this appears to cause cumulative loads about 9% greater than the sum of the static wheel loads on the roads, and on rough roads about 15% greater. Assuming road wear is proportional to the fourth power of the wheel loads, these load concentrations imply increases of 41% and 75% respectively. The weigh-in-motion results suggest even larger effects, but these are preliminary and require further calibration of the sensors before they can be regarded as reliable.

The effect of the spatial concentration of dynamic loads is additive to the effects of randomly distributed dynamic loads predicted by Eisenmann (1975). There can be little doubt that Eisenmann's predictions substantially underestimate the effect of dynamic wheel loads on road wear. It is therefore even more worthwhile than had previously been thought to improve the suspensions of heavy vehicles to reduce dynamic wheel loads.

6 ACKNOWLEDGEMENTS

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